K4D Knowledge, evidence and learning for development

Monitoring Air Quality in Low-Income and Lower Middle-Income Countries

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Question

How (and to what extent) is air quality monitored in low- and lower middle-income countries, and how effective is this data used?

Contents

1. Summary

This rapid literature review surveys academic and grey literature on air quality monitoring in low-income (LICs) and lower middle-income countries (LMICs). It draws heavily on three key sources of information. The World Bank (Awe et al., 2017) led report ‘Filling the Gaps: Improving Measurement of Ambient Air Quality in Low and Middle Income Countries’, the Health Effects Institute’s (2019) report on the ‘State of Global Air’, and the interdisciplinary work of the University of Birmingham led ‘A Systems Approach to Air Pollution’ (ASAP). It also profiles the work of Air Qo in Uganda as an exemplar of the rapidly evolving, locally led, air quality monitoring work underway in the global south.

Air pollution is a global environmental health threat, contributing to an estimated 3-7 million deaths per year (Lelieveld et al., 2015; WHO, 2014). Whilst various types of air pollution exist, particulate matter air pollution contributes most to global burden of disease. The effects of air pollution on human health are well documented in a range of epidemiological studies; exposure increases the risk of lung cancer, heart disease, bronchitis, and other cardiorespiratory conditions.

Despite links between exposure to indoor and outdoor air pollution and negative health impacts, there is paucity of long-term, appropriately calibrated data measuring air quality in LICs and LMICs. In particular, the apportionment of different pollution sources, e.g. vehicular emissions, industrial sources, and dust, to the overall pollution burden is often lacking. There is also a lack of evidence as to how these contributions vary between urban, peri-urban and rural environments and, indeed, within these as well as over time.

A number of methods of air quality monitoring are utilised to assess levels of air pollution. This includes ground level quality monitoring, which is well established in the global north, however, coverage in the global south is more variable. Other approaches are also available. A description of these is included below:

- **Ground-level Monitoring**: Air pollution is traditionally monitored by reference or regulatory grade monitoring stations that take accurate measurements, are used to build a long term understanding of air quality, and show compliance with national air quality standards. Given the size and cost of these devices most cities can only afford limited numbers. Low cost sensor-based technology offers an alternative for ground level air quality monitoring that is cost effective, mobile, and flexible. Such devices are proliferating, and have varying quality and accuracy. Furthermore, there are issues associated with their long-term durability, the technical skills required to use and maintain them, and the potential for erroneous monitoring. By calibrating and cross-referencing to reference/regulatory stations quality concerns can be addressed, but not fully overcome.
- **Satellite Remote Sensing**: Satellite-based remote sensing of air quality offers the prospect of daily observational information for most locations in the world. Satellite sensors measure interference in the light energy reflected or emitted from the Earth, which is used to calculate concentrations of air pollutants, such as particulate matter, nitrogen dioxide, carbon monoxide, and ozone. Challenges associated with this approach include lack of a universally accepted methodology, the effect of humidity, the coarse spatial resolution, the effect of clouds, deserts, snow, dust, and complex topographies. Measurements cannot be taken at night (a particular issue when considering that air quality, in many locations, declines significantly during the evening).

- **Air pollution modelling**: It is possible to model air pollution over larger geographic domains via the combination of ground level monitoring data and the application of modelling systems, such as WRF-CHIMERE, which simulates weather and the main pollutant dispersion patterns. The ASAP research team at the University of Birmingham have utilised this modelling approach, despite the small amount of historical input data, to reproduce real world air pollutant concentrations, with a degree of accuracy. The approach is relatively nascent and requires further testing, uptake may be constrained by technical and infrastructure considerations (cloud bases computing may address some of these) and is dependent on the quality of other sources of data. Modelling is very advanced for some regions, but less so for others.
- **Visibility as a proxy for air pollution**: Long term visibility measurements can be used for a proxy for air pollution. Visibility data is routinely collected at airports globally (in some cases from the 1950s to present day). Historic visibility is inversely proportional to the amount of particulate matter present in the air i.e. declining visibility correlates closely with increasing levels of air pollution. This approach provides a sense of trends in air quality over time but is unable to provide insight into current levels, or within area variations.

Air pollution affects all regions of the world, in a context of rapid urbanisation, the WHO estimated that between 2008 and 2013, urban air pollution levels increased by 8% and are expected to rise further given rapid urban development. Crop burning in Asia, agricultural production and mining may also cause air pollution in peri-urban and rural areas. Populations in low-income cities are most impacted. According to the latest air quality database, 97% of cities in LICs and LMICs with over 100,000 inhabitants do not meet WHO air quality guidelines. Risks associated with air pollution pose a particular threat to the young and aging and it is reported that around 90% of global air pollution deaths occur in LICs and LMICs (Awe et al., 2017: 16).

Whilst the majority of studies exploring air pollution monitor outdoor levels, indoor air quality is also a concern, particularly in households where vulnerable groups may be present. In many countries, people burn solid fuels (such as coal, wood, charcoal, dung, and other forms of biomass, like crop waste) to cook food and to heat and light homes. This practice generates high concentrations of pollutants in and around the home. In 2017, 3.6 billion people (47% of the global population) were exposed to household air pollution from use of solid fuels for cooking. These exposures are most common in SSA, South Asia, and East Asia (HEI, 2019: 8).

Despite concerted efforts to manage air quality globally, air pollution remains one of the world's largest environmental health risks (Longhurst et al., 2016). A holistic approach is required for effective intervention that considers different sources of air pollution and addresses the related socio-economic and health problems. Air quality management policies are expected to protect public health and to remove many of the adverse socio-economic impacts that are associated with air pollution. However, evidence continues to show that air quality management policies are failing even in the global north despite strong commitments at different scales of government

2. Air pollution: an introduction

Air pollution is a global environmental health threat contributing to an estimated three million deaths per year worldwide (Lelieveld et al., 2015). The Global Burden of Disease project (World Bank & IHME, 2016) estimates a figure for premature deaths closer to 5.5 million (one in every ten and the fourth highest factor for causing early death). The most extreme estimates are presented by the World Health Organisation (WHO, 2014), reporting that in 2012 over seven million people died (one in eight of total global deaths) as a result of air pollution exposure.

The effects of air pollution on human health are well documented in a range of epidemiological studies; exposure increases the risk of lung cancer, heart disease, bronchitis, and other cardiorespiratory conditions (Kelly & Fussell, 2015). The economic cost of this health loss is also significant, the World Bank estimates that globally in 2013 air pollution led to US$5.11 trillion in welfare losses, and US$225 billion in lost labour income (World Bank & IHME, 2016). The World Bank concludes that air pollution "is not just a health risk but also a drag on development… causing illness and premature death, air pollution reduces the quality of life. By causing a loss of productive labour, it also reduces incomes" (ibid: 2).

Despite the costs associated with air pollution, stakeholders (public, private, and civil society) often fail to assign sufficient attention to the issue. This may be driven, in part, by the existence of contemporaneous concerns (for example tackling poverty, addressing inequality, and driving economic growth), the challenge of associating current air pollution levels with future impacts, and the paucity of data pertaining to past, current and future air quality levels.

Available evidence suggests that air pollution will worsen in coming years and exert an increasing toll on public health in many cities. In a context of rapid urbanisation, the WHO estimated that globally, between 2008-2013, urban air pollution levels increased by 8% and are expected to rise further given continuing rapid urban development[1]. Renewed efforts are therefore required to sensitise individuals to the scale of the air pollution challenge and to encourage action to address the issue.

When experts discuss air pollution, they are typically referring to a mixture of solid particles and gases in the air stemming from human activity (i.e. anthropogenic sources). Car emissions, chemicals from factories, dust, pollen, and mould spores may be suspended as particles. Ozone, a gas, is a major part of air pollution in cities. Air pollution is typically separated into two categories: outdoor (ambient) and indoor (e.g. household) air pollution.

Outdoor air pollution involves exposures that take place outside of the built environment. Examples of outdoor air pollutants include:

- Fine particles produced by the burning of fossil fuels (i.e. the coal and petroleum used in energy production)
- Noxious gases (sulphur dioxide, nitrogen oxides, carbon monoxide, chemical vapours, etc.)
- Ground-level ozone (a reactive form of oxygen and a primary component of urban smog)
- Tobacco Smoke

Indoor air pollution involves exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust. Examples include:

- Gases (carbon monoxide, radon, etc.)

[1] https://www.who.int/news-room/detail/12-05-2016-air-pollution-levels-rising-in-many-of-the-world-s-poorest-cities

- Household products and chemicals
- Pollutants originating from household activities (e.g. cooking, heating and lighting)
- Building materials (asbestos, formaldehyde, lead, etc.)
- Indoor allergens (cockroach and mouse dropping, etc.)
- Tobacco smoke
- Mould and pollen

In some instances, outdoor air pollution can enter indoor environments by way of open windows, doors, ventilation, and vice versa.

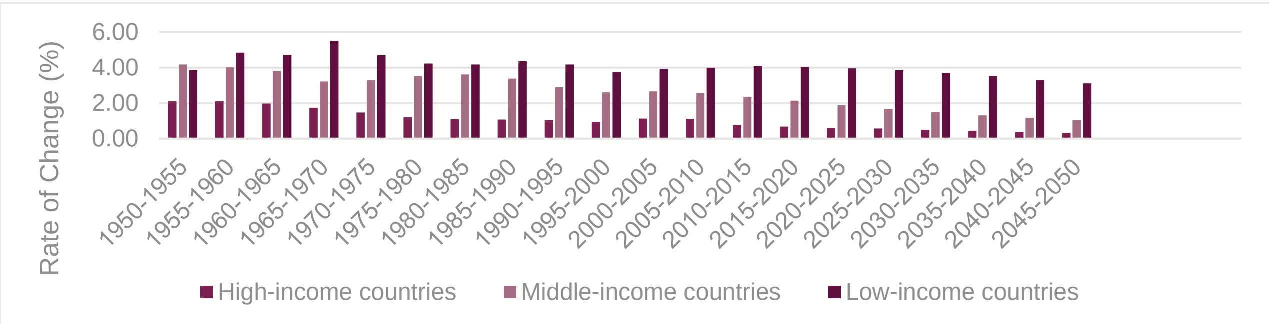
Two main pollutants are commonly considered key indicators of air quality: fine particle pollution: particulate matter measuring less than 2.5 micrometres in aerodynamic diameter, (often referred to as airborne particulate matter or $PM_{2.5}$) and ground-level (tropospheric) ozone. This paper will focus predominantly on $PM_{2.5}$ with a less developed discussion of ozone and carbon monoxide. The $PM_{2.5}$ size fraction is the focus of this study since it has greater association with detrimental health outcomes. In 2017, the Health Effects Institute estimated that 92% of the world's population lived in areas that exceeded the WHO guideline for $PM_{2.5}$ (see box 1[2]).

Increasing levels of air pollution are considered a matter of concern in many countries, particularly in the global south linked to population growth, urbanisation and the proliferation of sources of pollution (particularly transport). Urbanisation, in particular, is identified as a global trend exerting an increasing impact on society. It is broadly accepted that for the first time, the majority of the world's population lives in what can loosely be classified as 'urban areas'. In 2014, an estimated 54% (around 3.8 billion people) lived in towns or cities (UNDESA, 2014: 1). By 2050, 66% of people are projected to be living in urban areas, with the highest rates of urban growth expected in LICs and MICs (ibid.).

Box 1: ***Particulate Matter World Health Organisation Guidelines***

$PM_{2.5}$	10 µg/m³ annual mean
	25 µg/m³ 24-hour mean
PM_{10}	20 µg/m³ annual mean
	50 µg/m³ 24-hour mean

*Figure 1****: Average Annual Rate of Change of the Urban Population, 1950-2050 (per cent) (UNDESA Data)***[3]



[2] Licensed under CC BY-NC-SA 3.0 IGO

[3] https://population.un.org/wup/Download/Files/WUP2018-F06-Urban_Growth_Rate.xls

Box 2: ***How PM$_{2.5}$ Exposure is Estimated***

HOW PM$_{2.5}$ EXPOSURE IS ESTIMATED

Particulate matter concentrations are measured in micrograms of particulate matter per cubic meter of air, or μg/m^3. Many of the world's more developed countries monitor PM$_{2.5}$ concentrations through extensive networks of monitoring stations concentrated around urban areas. These stations provide continuous hourly measurements of pollution levels, offering a rich source of data that has served as the foundation for most studies of the potential health effects of air pollution and for management of air quality.

While these data sources are valuable, on-the-ground air quality monitoring stations are few and far between in the rapidly growing urban areas of countries at low and middle levels of development, as well as in rural and suburban areas throughout the world. To fill the gaps and provide a consistent view of air pollution levels around the world, scientists combine available ground measurements with observations from satellites and information from global chemical transport models.

Using this combined approach, scientists systematically estimate annual average concentrations of PM$_{2.5}$ across the entire globe divided into blocks, or grid cells, each covering 0.1° × 0.1° of longitude and latitude (approximately 11 km × 11 km at the equator). To estimate the annual average PM$_{2.5}$ exposures for the population in a specific country, scientists combine the concentrations in each block with the number of people living within each block to produce a population-weighted annual average concentration. Population-weighted annual average concentrations are better estimates of population *exposures*, because they give greater weight to the air pollution experienced where most people live.

Source: HEI, 2019: 4, https://www.stateofglobalair.org/sites/default/files/soga_2019_report.pdf

Box 3: ***How Ozone is Estimated***

HOW OZONE EXPOSURE IS ESTIMATED

Ozone concentrations are measured in parts per billion (ppb). When assessing exposure to ozone, scientists focus on measurements taken in the warm season in each region, when ozone concentrations tend to peak in the mid-latitudes (where most epidemiological studies have been conducted), rather than on annual averages. Like PM$_{2.5}$, ozone concentrations are measured in more-developed countries using extensive monitoring networks, but many parts of the world do not have such networks. Consequently, the GBD project has historically relied solely on chemical transport models to estimate ozone concentrations around the world in a consistent way.

This year, the GBD project updated and improved its methods for estimating ozone concentrations in two ways. First, the assessment now focuses on the seasonal 8-hour daily maximum concentrations instead of the 1-hour daily maximum concentrations used historically, because the 8-hour daily maximum is the metric used to characterize exposure in the most recent epidemiological studies of ozone's health effects (see Additional Resources). *Season* is defined by the 6-month period with highest mean ozone concentrations.

Second, this year's estimates have been strengthened by combining a blend of multiple chemical transport models with ozone measurements from a comprehensive database of measurements created as part of the Tropospheric Ozone Assessment Report (see Additional Resources). This approach has enabled correction for differences relative to observed values and the estimation of uncertainty in the model predictions.

GBD researchers combined the data from these updated models with population data to estimate "population-weighted seasonal average 8-hour maximum ozone concentrations" following the same process used for PM$_{2.5}$.

Source: HEI, 2019: 7, https://www.stateofglobalair.org/sites/default/files/soga_2019_report.pdf

Air pollution in low and middle-income countries

Air pollution affects all regions of the world. However, populations in low-income cities are considered to be the most impacted. According to the latest air quality database, 97% of cities in low- and middle- income countries with more than 100,000 inhabitants do not meet WHO air quality guidelines. In high-income countries, that percentage decreases to 49%[4].

With increasing numbers living in towns and cities, much existing urban infrastructure is struggling to cope with the increased demands of urban residents. In many contexts, rapid expansion and growth has led to urban and suburban sprawl i.e. the unrestricted growth of housing, commercial development, and roads. Urban sprawl is a term that also relates to the social and environmental consequences associated with this form of development. Urban sprawl is often associated with longer commutes, increased traffic congestion and air pollution.

Due to its different sources and removal processes, air pollution concentrations in cities, and surrounding peri-urban and rural areas, are highly heterogeneous. The multi-scalar and interdependent nature of urban air pollution (indoor-outdoor) also presents a complex landscape for air quality studies and has particularly significant impacts on certain vulnerable groups that face a higher risk of poverty and social exclusion than others (Avis & Khaemba, 2018; Avis et al, 2018; Avis et al; 2020).

Rapid urbanisation, increasing vehicle ownership and poorly enforced air pollution regulation has been accompanied by worsening air quality in many LICs and LMICs (Raje et al., 2018). Exposure to air pollution is widely linked to the degradation of public health, leading to increased incidences of asthma, respiratory disease, heart disease and lung cancer. These risks pose a particular threat to the young and aging. It is reported that circa 90% of global air pollution deaths occur in low to middle income countries (LMICs) (Awe et al., 2017: 6).

Despite links between exposure to indoor and outdoor air pollution and negative health impacts, there is paucity of long term, appropriately calibrated data measuring air quality in LICs and LMICs. In particular, the apportionment of different pollution sources, e.g. vehicular emissions, industrial sources and dust, to the overall pollution burden is often lacking (Pope & Blake, 2017). There is also a lack of evidence as to how these contributions vary between urban, peri-urban and to rural environments and, indeed, within these (Pope et al., 2018).

In many countries, governments, multi-lateral organisations and the private sector are increasingly motivated to take action on pollution. Unfortunately, there is a critical lack of air quality data. Whilst countries can take action without making substantial investments in measurements systems, however, any robust air quality management system should include a measurement component to address country-specific policy objectives and document trends over time. Capacity and capability across countries varies significantly. Awe et al. (2017) provide a typology of country types and associated monitoring constraints.

[4] https://www.who.int/airpollution/data/cities/en/

Table 1: ***Country types and Monitoring Constraints***

Country Type	Electricity	Laboratory and Analytical Capacity	Data Management Capacity	Staff Size	Staff Capacity	Financial Resources
1	No electricity available at site	None	Limited, e.g., individual computers	Fewer than 10 air focused staff	Basic technical training; some technical or analytical capacity may exist, non-existent or inadequate practical experience	None, donor dependent
2	Sporadic	Limited	Moderate, e.g., dedicated computers with backup	Fewer than 25 air focused staff	Basic technical training, some advanced technical or analytical capacity, limited practical experience	
3	Regular, some outages	Access to, or conducts own limited lab analysis	Dedicated data computers or servers, backup and data sharing agreements	At least 50 air focused staff	Some advanced technical training in addition to specialists in monitoring, emission inventory, some but inadequate technical experience	Some central funding, but significant donor funded projects
4	Consistent, infrequent outages	Access to or conducts own advanced lab analysis	Dedicated data computers, QA procedures, secure data backup and data sharing agreements	At least 75 air focused staff	Some advanced technical training in addition to specialists in monitoring, emission inventory, air quality management	Centrally funded, some donor support
5	Consistent	In-house advanced lab analysis	Dedicated data computers and in-house data servers, secure backup and online data	Over 100 air focused staff	Advanced technical training in addition to specialists in monitoring, emission inventory, air quality management, communications, data management, economics etc.	Centrally funded, including inhouse research

Source: Awe et al., 2017: 14, licensed under Creative Commons Attribution 3.0 IGO (CC BY 3.0 IGO)

Air Quality Indices

An air quality index (AQI) identifies limits on the amount of a given pollutant in the air. The standards are designed to protect people's health and have been calculated to allow a margin for people most at risk e.g. the young and old and people with pre-existing health conditions. The ambient air quality standards most often utilised include those developed by the European Union, the United States and the WHO. The WHO air quality standards are not legally binding,

Table 2: ***Air Quality Indices (India, Europe, USA)***

India	Europe	USA
Good (0–50)	Very Low (0–25)	Good (0-50)
Satisfactory (51–100)	Low (25-50)	Moderate (51-100)
Moderately polluted (101–200)	Medium (50-75)	Unhealthy for Sensitive Groups (101-150)
Poor (201–300)	High (75-100)	Unhealthy (151-200)
Very poor (301–400)	Very High (>100)	Very Unhealthy (201-300)
Severe (401-500)		Hazardous 301-500

Source: Author's own, data taken from Wikipedia, https://en.wikipedia.org/wiki/Air_quality_index

Air quality indices are based on concentrations of a range of pollutants, commonly including Ozone, Nitrogen Dioxide, Sulphur Dioxide, $PM_{2.5}$ and PM_{10}. The breakpoints between index values are defined for each pollutant separately and the overall index is defined as the maximum value of the index. Different averaging periods are used for different pollutants. The US Environment Protection Agencies (US EPA) AQI has been used by a number of research programmes (including ASAP) to communicate levels of air pollution.

3. Ambient (outdoor) air quality monitoring in LICs and LMICs

Ambient air pollution is driven by various factors, notably rapid urbanisation, increased motorisation and energy use, burning of wastes and solid fuels (including for domestic cooking and heating). Some regions are experiencing an upward trend in emissions. As noted above, many countries in the global south lack reliable data on air quality to provide the basis for informing decision making and action to reduce air pollution and mitigate its health impacts. There is a significant air quality measurement and data gap at the LIC and LMIC country-level and a need to build institutional systems to address these gaps and create local strategies to reduce emissions in these countries (Awe et al, 2017). That data that does exists, highlights that cities in the global south particularly in South and South East Asia are regularly identified as having the worst air quality globally (see table 3). A note of caution should be sounded, i.e. that these figures are based on readily accessible data – given the proliferation of regulatory grade air quality monitoring (particularly in India and China) – it is unsurprising that these countries feature prominently. Whilst levels are likely lower across other African and Asian countries, comparisons are challenging given limited coverage of monitoring.

The measurement gap is considered highly problematic, because while reliable and sustainable air quality measurement is only one element of comprehensive air quality management (AQM), it serves as the foundation for many of the subsequent steps in the AQM process (Awe et al, 2017). Measurement data provides the underpinnings for: assessing the extent of air pollution; identifying sources of air pollution; understanding how air pollutants are transported and dispersed in the environment; identifying alternative interventions and selecting economically efficient interventions to reduce human exposure at the local level; evaluating and tracking the implementation of interventions; enforcing compliance with air quality standards; taking corrective measures where needed; and activating contingency plans. Further, each country will have its own set of sources, pollution mix and governance systems, thus requires its own capacity to generate local data and knowledge needed to manage air quality (Awe et al., 2017).

Table 3: ***Worlds Most polluted cities 2018 (IQ Air – Air Visual)***

City (Country)	2018 Average
Gurugram (India)	135.8
Ghaziabad (India)	135.2
Faisalabad (Pakistan)	130.4
Faridabad (India)	129.1
Noida (India)	125.4
Patna (India)	123.6
Noida (India)	119.7
Hotan (China)	116
Lucknow (India)	115.7
Lahore (Pakistan)	114.9

Source: Author's own, data taken from https://www.iqair.com/us/world-most-polluted-cities

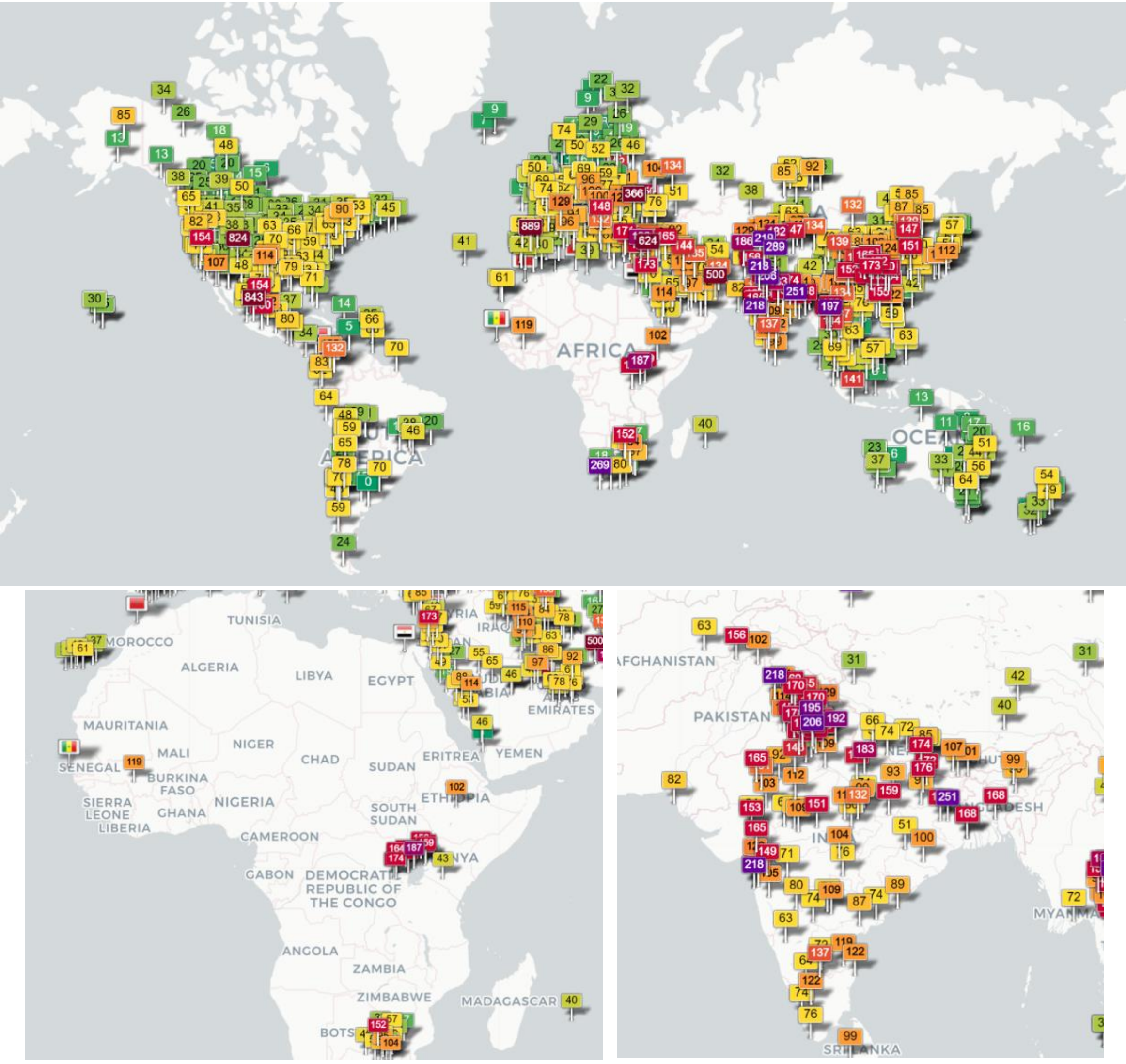
This paucity of information also means that the residents of these countries may not be well informed about the dangers of air pollution, nor have the information needed to advocate for mitigation policies. Awe et al. (2017) assert that closing the measurement gap can enable LMICs to meet both local development and public health objectives and the global goals under the SDGs. To illustrate the paucity of regulatory grade air quality monitoring in certain countries image one presents a screen shot of the Real-Time Air Quality Index, which reports air pollution data gathered from air quality monitors across the world. It is important to note that this image is not an exhaustive catalogue of air quality monitoring ongoing globally and excludes a wide range of spot measurement campaigns.

Whilst coverage has increased substantially in recent years, data for much of Africa and certain South Asian countries is limited or absent. More broadly, given the cost of regulatory grade air quality monitoring stations these are limited in their coverage:

- Monitoring locations tend to be located in capital or major cities and often in areas where air pollution may be lower (i.e. more affluent areas). US Environment Protection Agency, for example, have located air quality monitors in a number of embassy's across the global south. Rapidly urbanising secondary and tertiary cities are often poorly covered or excluded.

- The data tends to preclude analysis of within city variations i.e. between urban roadside, urban background areas (Pope et al., 2018) or of air pollution levels at locations where air quality may be particularly poor such as dumpsites (see Avis et al., 2018) or bus stations (see Avis et al., 2019) etc.
- The data also precludes an analysis of how city air quality may impact on peri-urban and rural areas (Pope et al., 2018).

*Image 1: **World's Air Pollution: Real-Time Air Quality Index***



Source: World Air Quality Index project and worldwide EPA, http://waqi.info/

*Table 4: **Spot Count of Air Quality Monitoring Devices in FCDO Focus Countries (Bilateral Programmes)***

Uganda	50+	**Kenya**	2	**Liberia**	0	**South Sudan**	0
Kyrgyzstan	16	**Afghanistan**	1	**Malawi**	0	**Sudan**	0
Nepal	16	**Iraq**	1	**Mozambique**	0	**Syria**	0
Indonesia	8	**Myanmar**	1	**Nigeria**	0	**Tanzania**	0
Pakistan	6	**Tajikistan**	1	**OPT**	0	**Yemen**	0
Ethiopia	3	**DRC**	0	**Rwanda**	0	**Zambia**	0
Bangladesh	2	**Ghana**	0	**Sierra Leone**	0	**Zimbabwe**	0

Source: Author's own, data taken from https://waqi.info/

Significant advances have, however, been made with respect to air quality monitoring in recent years. These advances are based on a range of technologies, from extensive ground level monitoring networks to satellite and other remote sensing technologies. The below section provides a summary of these approaches. Of particular interest is the wok of the Makerere University based Air Qo who have established an extensive and expanding network of low-cost sensors across Uganda.

It is also important to note that outdoor air pollution varies over various time scales: diurnal, day of the week, seasonally, yearly and decadal. To really understand air pollution, you need measurements over all these timescales. Seasonal variation is particularly important because meteorological conditions can influence both the sources and loss processes of air pollution.

Ground-level Monitoring

The cost, complexity and effort involved in establishing regulatory-grade approaches to air monitoring has precluded the widespread installation and operation of air monitoring networks in many LICs and LMICs. Regulatory-grade approaches for monitoring air pollution require laboratory support capabilities for integrated filter methods, and reliable electricity as well as a degree of technical, financial and human resource capacity.

Sub-regulatory-grade continuous monitoring methods also exist, and are commonly classified as follows:

1) well-established non-regulatory-grade technology (WNT) are generally more portable and lower cost than regulatory-grade but have inferior accuracy and precision compared to regulatory-grade monitors,

2) emerging non-regulatory-grade technology (ENT), which have desirable attributes of being miniaturised and at a low purchase price, but their accuracy, reliability, longevity, and full cost of use are not well-established.

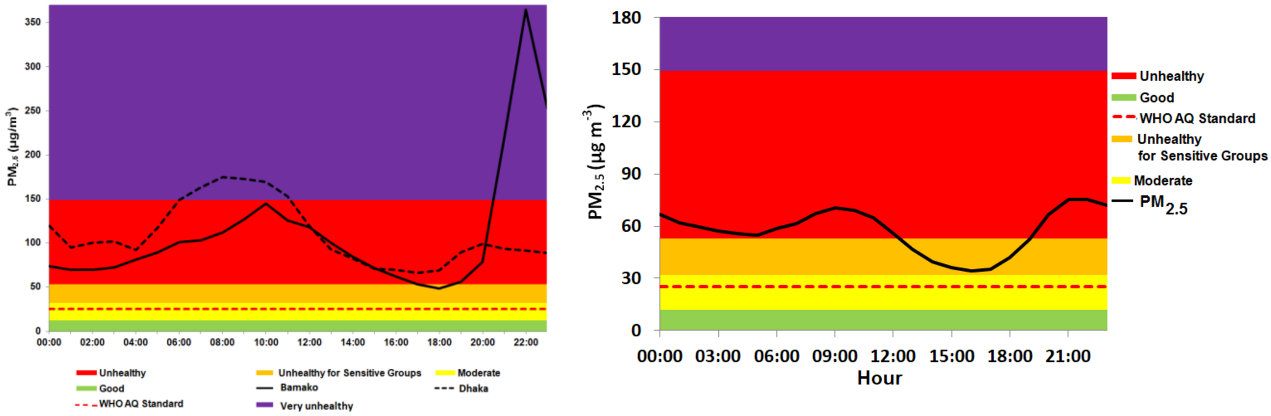
Table 5: ***Summary of detection approaches for $PM_{2.5}$***

Approach	Detection Approach	Strengths	Weaknesses
Integrated filter regulatory grade monitor	Particles are size-selected (impactor or cyclone), collected to a pre-weighed filter, then weighed after collection	Highest-fidelity measurement of particle mass concentration; laboratory analyses can include chemical composition. Expected technology working life exceeds 10 years.	24-hour samples; requires analytical laboratory capability, generally requires land power for long-term use.
Continuous, regulatory grade monitor	Particles are size-selected (e.g., cyclone) then measured through one of several types of methods - beta attenuation, tapered element oscillating microbalance, or optical detection	Continuous measurement, with data available typically on an hourly basis (some on a minute basis). Well established approach for regulatory use. Expected technology working life exceeds 10 years.	High cost of sampler; maintenance of monitor; power consumption generally requires land power for long-term use. Correlation factors needed for integrated filter regulatory-grade monitor.
Continuous, well established non-regulatory technology (WNT)	Particles are size-selected (e.g., cyclone), detected either optically or via beta attenuation. Sometimes includes on-board measurement of relative humidity to provide artefact correction.	Continuous measurement, with data available typically on the order of seconds to minutes. Lower cost, lower power consumption, and greater portability. Expected technology working life exceeds 5 years.	Less accurate than regulatory-grade monitors.
Continuous, emerging non-regulatory technology (ENT)	Particles are detected via either: 1) an optical particle counter, which sizes and counts the particles optically, or 2) without any sizing and measuring how the ensemble of particles scatter light.	Low purchase price point; miniaturized and low power consumption support small integrated ENT systems for dense sensor networks or portable monitoring.	Does not size-select for strictly <2.5um particles; performance under varying pollution mixtures and concentration levels is poorly known. Technology expected to degrade or fail in 1-2 years

Source: Awe et al., 2017: 17, licensed under Creative Commons Attribution 3.0 IGO (CC BY 3.0 IGO)

To contextualise air quality monitoring data from ground level devices, information is gleaned from monitors in select cities and mapped onto US EPA AQI (this analysis was contributed by an ASAP researcher at the behest of the author – the analysis should not be considered representative but rather illustrative and was undertaken with little notice):

Figure 2: ***Air Quality in select cities across the global south – Left = Bamako (Mali) and Dhaka (Bangladesh) and Right = Yangon (Myanmar)***



Source: ASAP-East Africa generated for this report, reproduced with kind permission

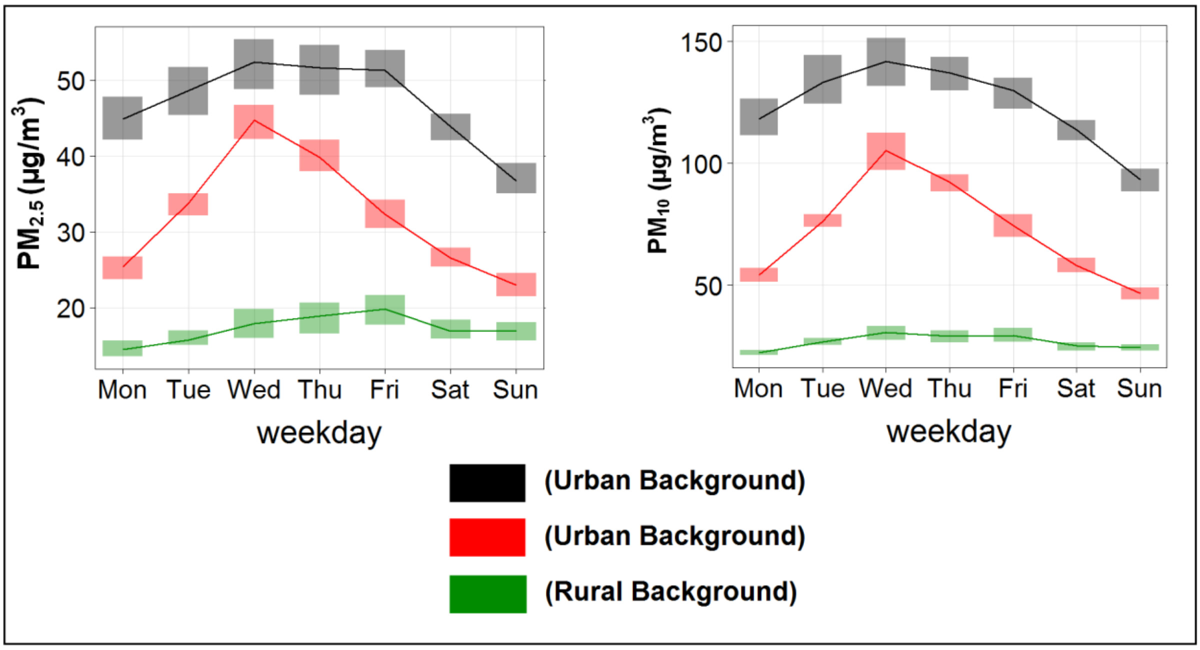
Low cost sensors

Given the cost of regulatory grade monitoring, much attention has focussed on the potential of low-cost sensors as a means of filling the data gap. Such devices offer the possibility of long-term measurements in LICs and LMICs. Many caveats are associated with such devices including their reliability, the cost of maintenance and the need for gravimetric calibration.

The ASAP research team and colleagues at Columbia University have critically appraised the utility of such devices (specifically those that have been calibrated). The calibration approach and the use of the Alphasense optical particle counters (OPC-N2) are discussed in Crilley et al. (2017) and Pope et al. (2018). The European Commission (Nd) has reviewed a range of sensors for cost point and accuracy.

The ASAP team have deployed low cost sensors in a number of contexts to monitor both indoor and outdoor air quality. Measurements have been collected using calibrated Alphasense OPC-N2, which records $PM_{2.5}$ and PM_{10} at ten-second intervals, aggregated to one-hour time steps. Low cost sensors can be deployed in an array of locations and allow for the monitoring of air quality in otherwise hard to reach areas. Analysis of data allows comparison between urban areas (i.e. urban roadside and urban background and rural areas) important for appraising how pollution may vary between areas.

Figure 3: ***Variation in average air quality levels across three monitoring sites in Nairobi (3 month measurement campaign (Pope et al., 2018 – analysis provided for this report).***



The approach also allows for innovation i.e. deployment indoors, in areas where pollution may be particularly poor (i.e. hotspots such as bus stations) and the combination of air quality data with GPS data to allow for dynamic (mobile) air quality monitoring on buses or taxis etc. Examples of work undertaken in the ASAP project include:

- Avis et al. (2020). Vulnerability Scoping Study - Low Income Households in Kampala
- Avis et al. (2019). Vulnerability Scoping Study - Addis Ababa Public Transport
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Satellite Remote Sensing

Satellite-based remote sensing of air quality offers the prospect of daily observational information for most locations in the world. Satellite sensors measure interference in the light energy reflected or emitted from the Earth, which is used to calculate concentrations of air pollutants such as PM, nitrogen dioxide, carbon monoxide, and ozone. In the case of particles, the satellite sensors measure the Aerosol Optical Depth (AOD) -- the degree to which light has been absorbed or scattered by particles in the atmosphere. Using geophysical models and statistical calibration, scientists continue to refine how they relate the satellite-based AOD observations to the surface concentration of $PM_{2.5}$. Targeted study of satellite observations of multiple atmospheric constituents over cities can facilitate the determination of spatial and temporal changes in air pollution.

Satellite observations can be used to identify changes in urban pollution due to nearby agriculture and fertilizer use (using NH_3), industrialisation (using NO_2, CO, and HCHO as a surrogate for volatile organic compounds), ozone chemistry (with HCHO:NO_2 ratios; e.g. Martin et al., 2004), aerosol abundance (using AOD), and aerosol optical properties (using AI). Results from such observations can provide context for the deployment of low-cost sensors.

Forthcoming research by Marais (forthcoming 2020) provides maps of annual mean tropospheric column NO_2 over East Africa for 2005 and 2016 to demonstrate the level information that can be obtained from satellite observations. Highest concentrations of NO_2, west of the cities of interest (Kampala, Addis Ababa and Nairobi), are due to biomass burning. The enhancement is lower in 2016 than 2005 that may indicate a trend in fire activity, or be driven by large inter-annual variability in precipitation (Andela & van der Werf, 2014). Anthropogenic features are more distinct in 2016 than 2005 and provide the means to identify pollution hotspots that warrant further investigation. These include air pollution hotspots focussed on Khartoum in Sudan and seaports in Kenya and Somalia. Nairobi and Addis Ababa are distinct from background and biomass burning NO_2, but are still an order of magnitude lower than NO_2 concentrations over megacities in North America and Europe, despite dramatic policy-driven declines in air pollution in those regions (Krotkov et al., 2016).

According to Awe et al, (2017: 18) there are several challenges in using satellite imagery, in particular this relates to converting the AOD to an estimate of particle concentration. Challenges include:

- **Lack of a universal methodology to determine relationship between AOD and surface concentrations**: Columnar aerosol optical depth is influenced by aerosol throughout the entire atmospheric column. Scientists have used the vertical distribution of aerosols from chemical transport models (such as GEOS-Chem) to infer the surface aerosol contribution to the columnar AOD to infer surface level PM.
- **Effect of humidity**: AOD is measured at ambient relative humidity, while ground-level $PM_{2.5}$ in reference monitors is usually measured at a controlled relative humidity.
- **Coarse spatial resolution**: the sensor observes an average value over a spatial resolution of a few kilometres (computation at finer resolution is more expensive).
- **Effect of clouds, deserts, snow, dust and complex topographies**: It is difficult to differentiate the particles on cloudy days or over particularly bright deserts and snow covered surfaces, and accuracy is unreliable in complex topographies such as mountainous areas, and in areas affected by natural dust and sea salt.
- **Measurements cannot be taken at night**. The satellites only pass over a specific place once a day, usually between mid-morning and early afternoon.

Air pollution modelling

Given practical constraints related to ground level air quality monitoring, attention has focussed on the potential of air pollution modelling to fill gaps. The ASAP research team have investigated air pollution using numerical modelling approaches (Mazzeo et al., nd; nd). This approach enables the reproduction of the main meteorological patterns, anthropogenic pollution emissions related to different sectors and the chemical and transport processes acting in the atmosphere**.** Efforts have focused on the following objectives:

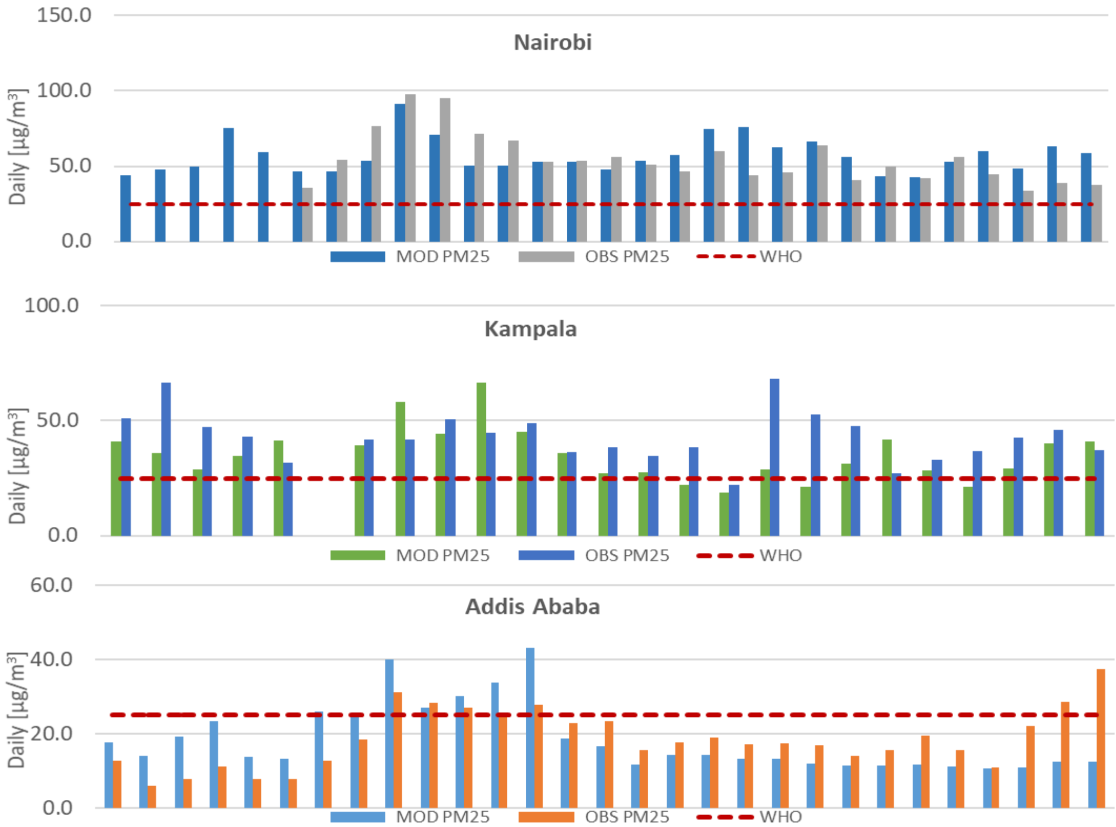
1. Manipulation of the available open source emissions inventories for East Africa to create a new up-to-date emission inventory.
2. Quantitative analysis of the impact of each anthropogenic emission sector.

3. Simulation of the main regional and local meteorological processes and air pollutant dispersion patterns for focus countries and cities.
4. Creation of reduced emissions scenarios, with a focus on the improvement of the urban road network, including: regular road maintenance, upgrading of urban road paving, and progressive electrification of the vehicle fleet.

Two modelling systems have been adopted for this purpose. The Highway Development and Management version 4 (HDM-4) reproduces the ground state conditions of the road network and enables the creation of alternative scenarios, according to the implementation of maintenance standards for road networks and modification in the vehicle fleet. Also, the model returns an economic analysis for the implementation of possible scenarios. The meteorological and chemical dispersion patterns are simulated by a modelling system made up by coupling the Weather and Research for Forecast model with the chemistry-transport model CHIMERE (hereafter WRF-CHIMERE).

The modelling system WRF-CHIMERE simulates weather and the main pollutant dispersion patterns for focus cities (other models for regional air quality modelling are available, but most are currently not well calibrated for African conditions). The ASAP research team have utilised the modelling system, despite the small amount of historical input data, to reproduce real world air pollutant concentrations, (Figure 4) with a degree of accuracy. Heat Maps relating the average concentrations of PM_{10} with the local regional county borders show how the majority of the urban areas of the three cities are affected by concentrations of PM_{10} higher than the WHO limits.

Figure 4: ***Daily time series relative to $PM_{2.5}$ concentrations from modelled data and from different observation sources: $PM_{2.5}$ for Nairobi comes directly from measurements made by the ASAP-East Africa project while $PM_{2.5}$ daily values for Addis Ababa and Kampala have been obtained by the local US Embassies.***



Source: Mazzeo et al. (n.d., p.20), licensed under Open Government Licence v3.0.

The results suggest air quality levels in urban East Africa can be modelled effectively. Going forward, more effort is required to improve the accuracy of the input data, which would result in improved model outputs. The high levels of air pollution observed and the extension of the poor air quality areas in the three cities highlight the importance of further scientific focus on the extent of the transport of air pollutants by local meteorology.

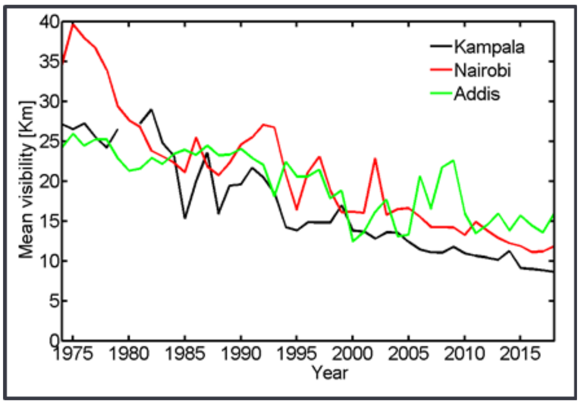
Despite the low quantity and quality of input data available for the work, the modelling system WRF-CHIMERE has shown good capabilities in reproduction of real-world air pollution levels. Additional input data from different research environments, as well as the training of local researchers in monitoring and modelling, represents a feasible option for increasing knowledge of and expertise in air pollution in East Africa.

Visibility as a proxy for air pollution

Globally, many cities in LICs and LMICs lack quality monitoring programmes even though they often have high levels of air pollution. The paucity of historic air pollution data in these locations makes it difficult to understand their current situation and to predict their future air pollution trajectory.

Whilst there exists a paucity of air quality data, available information illustrates that air quality is an issue of particular concern with air pollution threatening to undermine the development of inclusive, safe, resilient and sustainable cities. Long term visibility measurements can be used as a proxy for air pollution (see figure 5). Visibility data is routinely collected at airports globally (in some cases from the 1950s to present day). Historic visibility is inversely proportional to the amount of particulate matter present in the air i.e. declining visibility correlates closely with increasing levels of air pollution. Results collected by the ASAP research team suggests that increased populations, the crowding of motorised traffic onto roads and increased economic activity in focus countries has been accompanied by a gradual but steady decline in air quality. Using visibility as a proxy, since the 1970s to present, air pollution is estimated to have increased by 162, 182, and 62% in Kampala, Nairobi and Addis Ababa, respectively (Singh et al., 2020). Such an approach may provide an opportunity to identify cities where visibility has declined significantly and where efforts to address the causes and consequences of air pollution should be focused. It also flags the extent to which declining air quality is a long-term process linked to urban development and increased economic activity.

Figure 5: ***Long term visibility measurements from Addis Ababa, Kampala and Nairobi from 1970-2010***



Source: Singh et al. (2020, p.4), licensed under Creative Commons Attribution 4.0 licence.

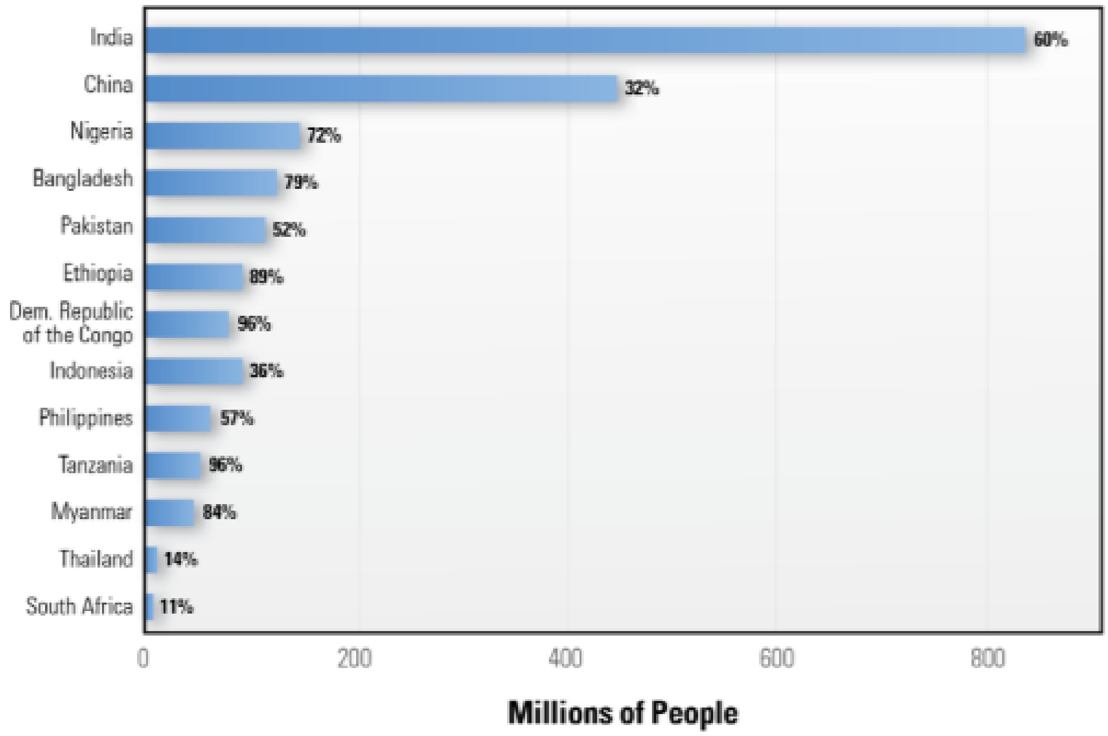
4. Indoor (household) air pollution monitoring in LICs and LMICs

Whilst the majority of studies exploring air pollution monitor outdoor levels, indoor air quality is also a concern, particularly in households where vulnerable groups may be present. Indoor air pollution is much more heterogeneous than outdoor air pollution and hence sampling strategies need to be carefully considered. As noted by HEI (2019), in many places, people burn solid fuels (such as coal, wood, charcoal, dung, and other forms of biomass, like crop waste) to cook food and to heat and light their homes. This practice generates high concentrations of pollutants in and around the home. In 2017, 3.6 billion people (47% of the global population) were exposed to household air pollution from the use of solid fuels for cooking. These exposures were most common in sub-Saharan Africa, South Asia, and East Asia (HEI, 2019: 8).

Results that focus on outdoor readings alone may fail to provide an accurate estimation of personal exposure given length of time spent indoors. Globally, a range of studies have highlighted that many households have health problems linked to poor indoor air quality, with recorded indoor air pollutant levels often exceeding outdoor levels. This has been found to be the case across East Africa when cooking with biomass occurs in small or space constrained homes (Tarekegn & Gulilat, 2018, Okello et al., 2018). Exposure to domestic cooking smoke is currently the world's single largest environmental health risk, responsible for circa 4 million early deaths each year, predominantly in LIC and LMIC settings[5].

Globally, whilst the number of people cooking with solid fuels has declined, disparities persist, and populations in the global south continue to suffer the highest exposure to HAP (HEI, 2019). In East Africa, many households rely on kerosene (paraffin) for cooking and lighting as well as charcoal or wood for cooking. In the poorest of households, the use of plastic waste, cloth rags and other unconventional fuels has been reported (Muindi et al., 2014).

Figure 6: ***Percentage of population exposed to household air pollution in 13 countries with populations over 50 million in which more than 10% of the population uses solid fuels for cooking***

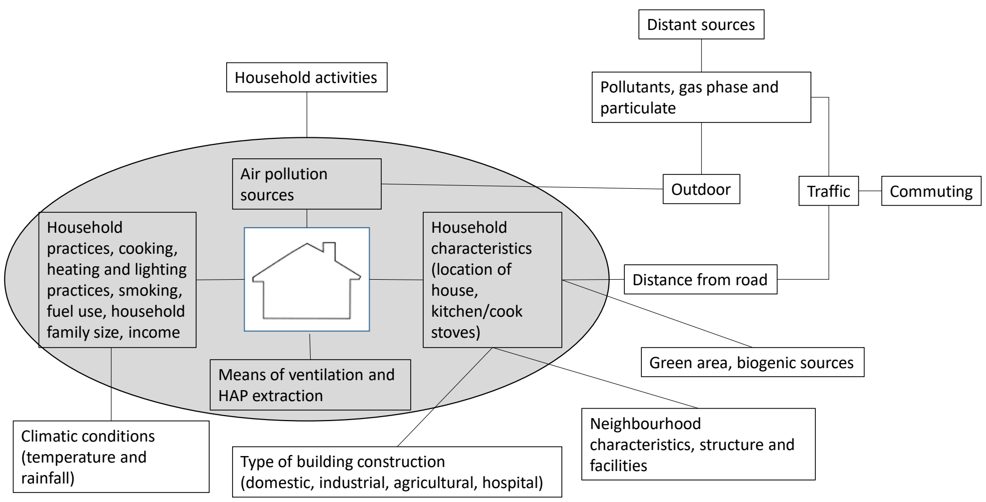


Source: HEI, 2019: 9, https://www.stateofglobalair.org/sites/default/files/soga_2019_report.pdf

[5] https://www.who.int/en/news-room/fact-sheets/detail/household-air-pollution-and-health

The home environment is a complex setting in which to undertake an assessment of air quality. Thermal comfort, air pollution sources, building characteristics and household tasks are factors influencing exposure (see image 4). These are in turn affected by other aspects inside and outside the home environment. Increased PM concentrations are often correlated with household activities, small room sizes, high occupation rates, and fuel usage (Bartington et al., 2017). Locations in close proximity to industrial areas, busy roads or sources of dust are likely to experience higher levels of air pollution (Kim et al., 2016).

*Image 4**: Representation of factors and linkages with possible impact on the indoor air quality in households - primary factors highlighted in the grey area***



Source: Avis et al., 2020: 22; adapted from Salthammer et al., 2016: 197, licensed under Open Government Licence v3.0.

Measuring household pollutant exposure is thus beset by complexity, it requires indoor assessment techniques, including efforts to estimate personal exposure. Most pollutants affecting indoor air quality come from sources inside buildings, although some may originate outdoors. Indoor sources include[6]:

- ***Combustion sources*** in indoor settings, including tobacco, heating and cooking appliances, and fireplaces can release harmful combustion by products such as carbon monoxide and PM.

- ***Cleaning supplies, paints, insecticides, and other commonly used products*** introduce many different chemicals, including volatile organic compounds, directly into the indoor air.

- ***Building materials*** are also potential sources, whether through degrading materials (e.g., asbestos fibres released from building insulation) or from new materials (e.g.,

[6] https://www.epa.gov/report-environment/indoor-air-quality

chemical off-gassing from pressed wood products). Other substances in indoor air are of natural origin, such as radon, mould and animal dander.

Outdoor pollutants can enter buildings through doors, windows, ventilation systems, and cracks in structures:

- ***Harmful smoke from chimneys or vehicular emissions*** can enter homes to pollute the air. In areas with contaminated ground water or soils, volatile chemicals can enter buildings through the same process.
- ***Volatile chemicals in water supplies*** can also enter indoor air when building occupants use water (e.g., during washing, cooking).
- ***People entering buildings*** can inadvertently bring in soils and dusts on their shoes and clothing from outdoors, along with pollutants that adhere to those particles.

See: *Table 6:* ***Emission parameter assumptions (Jeuland & Tan Soo, 2016: 19),*** ***https://www.cleancookingalliance.org/binary-data/ATTACHMENT/file/000/000/355-1.pdf***

The combustion of biomass for cooking purposes is a matter of particular concern, and the primary source of HAP in many households. Significant numbers rely on biomass fuels (wood, charcoal, crop residue, dung) for cooking or heating purposes. HAP resulting from the use of these fuels is of particular concern, given the overall prevalence as well as the intensity of exposure and the range of potential adverse health outcomes (see table 6 for emission estimates from a range of cooking appliances).

Interest in low income group's exposure to environmental risk factors, such as air pollution, has increased in recent years. A number of studies have focused on $PM_{2.5}$ in terms of mass and source contribution in both indoor (Okello et al., 2018; Simoni et al., 2015; Bentayeb et al., 2015; Mendes et al., 2015) and outdoor settings (Simoni et al., 2015; Rajagopalan et al., 2018). Of particular interest is the work of Okello et al. (2018) who gathered data on 24-hour personal exposure to HAP across six groups defined by age and gender (young children, young males, young females, adult males, adult females, and elderly) in rural households in Ethiopia and Uganda. Findings highlighted in figure 7 suggests that adult females are most exposed to HAP followed by young females and infants. This likely relates to household activities – namely cooking – undertaken by these groups or dependency on mothers. These findings also suggest that women and girls will likely be most susceptible to the long-term health effects of HAP exposure, particularly in households that are dependent on more polluting fuels.

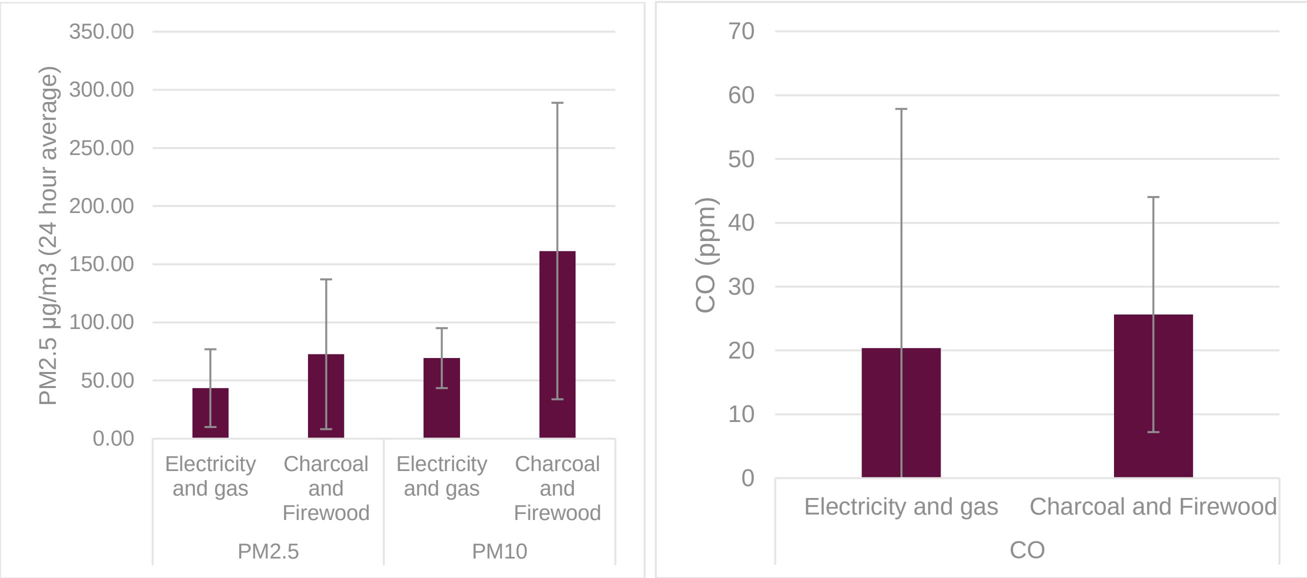
See: Figure 7: ***Comparison of mean 24 hour $PM_{2.5}$ μg/m^3 among the six age groups in Ethiopia and Uganda (Okello et al., 2018: 433),*** ***https://www.sciencedirect.com/science/article/pii/S0160412018301855?via%3Dihub***

Quantifying the contribution of household exposure with observed health symptoms, however, poses a number of challenges. In addition to ascertaining the impact of non-household-based exposures, air pollutant exposure is influenced by daily patterns of activity during and outside periods spent at home hours which make it difficult to compare the contribution of household-based and non-household-based exposures (WHO, 2000).

Indoor (household) air quality monitoring in East Africa

The ASAP programme have undertaken household air quality monitoring across East Africa to ascertain exposure to air pollutants. Whilst, the focus was on $PM_{2.5}$, it is important to note that household practices may also lead to elevated levels of other pollutants (namely PM_{10} and Carbon Monoxide CO). Figure 8 provides a comparison of households that reported using charcoal or firewood for cooking versus LPG or electricity. Figure 9 below demonstrates the extent to which energy poverty exposes households to significant risk with levels of exposure higher across all pollutants monitored for those households who used charcoal and firewood.

Figure 8: ***Mean and standard deviation for selected pollutants monitored in households in Namuwongo (Kampala) (Avis et al., 2020: 24)***



Source: Avis et al., 2020: 22, licensed under Open Government Licence v3.0.

Alongside this comparison, figure 7 contrasts two households (one charcoal and firewood and one LPG and electricity) over the same 24-hour periods monitored. Across the monitored period, the charcoal and firewood household recorded an average level of $PM_{2.5}$ of 59.1 µg/m^3 and the LPG and electricity household 23.54 µg/m^3. Whilst these figures are significant, it is when one considers peak levels of air pollution that we get a true sense of the

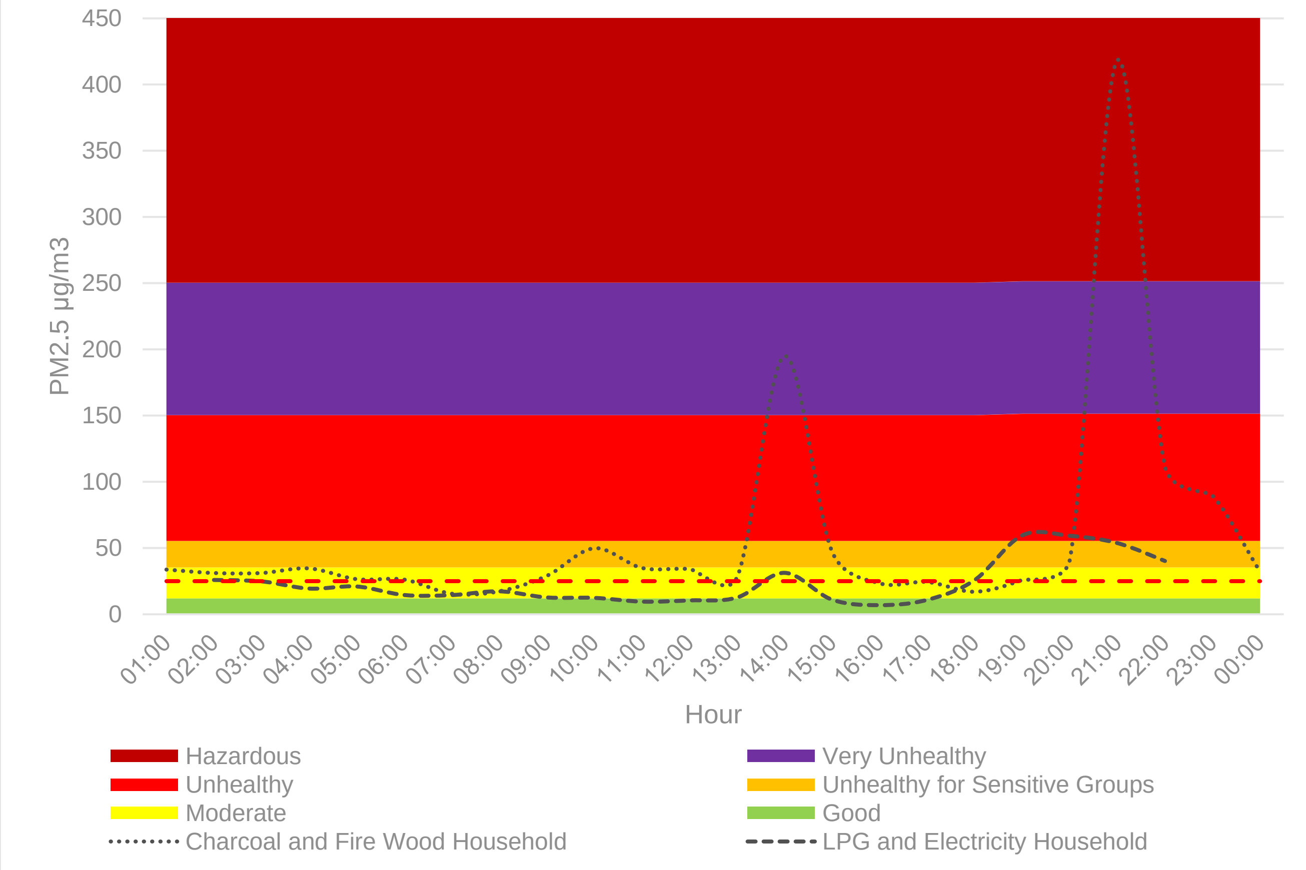
Table 5: ***Average indoor $PM_{2.5}$ (µg/m^3) daily concentrations (LPG and Electricity versus Charcoal and Firewood)***

Average $PM_{2.5}$ (µg/m^3) daily concentration (LPG and Electricity)	Average $PM_{2.5}$ (µg/m^3) daily concentration (Charcoal and Firewood)
23.54 µg/m^3	59.1 µg/m^3

Source: Avis (2018, p.23) , licensed under Open Government Licence v3.0.

impact charcoal and firewood has on HAP. In the charcoal and firewood house, peak concentration recorded during the monitoring period was 418.38 µg/m^3.In contrast, the LPG and

Figure 9: ***HAP PM$_{2.5}$ Monitored in Namuwongo – Households that use Charcoal and Firewood versus LPG and Electricity***



Source: Avis (2018, p.25) , licensed under Open Government Licence v3.0.

electricity household recorded a peak level of 59.61 µg/m^3. Over the 24-hours air quality was monitored, pollution levels in the first household were on average considered unhealthy and peaked at hazardous levels according to the US EPA AQI and were significantly above the WHO guidelines for PM$_{2.5}$. In contrast, readings in the LPG or electricity household levels of air quality were considered to be moderate peaking at unhealthy levels. Indoor air quality in those households that use charcoal or firewood is thus considered to be an issue of particular concern. To contextualise these readings, figure 9 maps both outdoor and indoor air pollution on the US EPA air quality index during the day monitored.

5. Evidence informed air quality management

Despite concerted efforts to manage air quality globally, air pollution still remains one of the world's largest environmental health risks (Longhurst et al., 2016). A holistic approach is required for effective intervention that considers the different sources of air pollution and addresses the related socio-economic and health problems. Air quality management policies are expected to protect public health and to remove many of the adverse socio-economic impacts that are associated with air pollution. However, evidence continues to show that air quality management policies are failing even in the global north despite strong commitments at different scales of government (Brunt et al., 2016).

Concerted efforts aimed at managing air quality must not only consider the diagnosis of air quality problems, but the implementation of holistic actions targeted at both public health and wider environmental impacts. Moreover, the current situation raises cause for concern, particularly in the global south, with alarming rates of air pollution problems, and yet poor air quality management practices. Many African countries have developed comprehensive legislation requiring its control, but struggle to enforce the legislation effectively and link it to the other economic, urban and political challenges (Bryson et al., 2018).

A particular challenge relates to the use of what evidence is available. Sutcliffe and Court (2006: 5) identified some important considerations for the use of evidence by policy makers, these include:

- **Evidence use does matter**: better use of evidence in policy and practice can help reduce poverty and improve economic performance in developing countries.
- **Policy should be informed by a wide breadth of evidence**, not just empirical data. Key issues include the quality, credibility, relevance and cost of the policy.
- **Evidence is needed in all the different components of policy processes** – and in different ways in each component.
- **Various constraints (time, capacity, cost)** will affect the mechanisms available for mobilising evidence for policy in developing countries.
- **Policy processes are inherently political**.

Whilst it is difficult to ascertain the extent to which air quality data is used across LICs and LMICs, it is clear that a number of factors will collectively be impeded or facilitate evidence informed approaches to air quality management.

- **Human Resource**: Many countries in the world lack sufficient resources to mainstream air pollution data into government policy. This includes the lack of staff in dedicated environmental offices as well as staff conversant with air quality data across over government departments e.g. urban planning.
- **Financial Resource**: Air quality management and the monitoring of air pollutants can be expensive and many governments and both national and local levels lack the funds to undertake widespread air quality monitoring. This often leads to the focus on particular urban areas. Financial resource constraints may also impact on the ability to purchase hardware to monitor or analyse air pollutants
- **Technical Capacity**: Countries may lack sufficient technical capacity to undertake air quality monitoring and use data collected to manage air pollution. This includes training in approaches to monitoring and source apportionment, to the modelling of air pollution or to ascertaining its health impact.

Filling the data gaps

Awe et al. (2017: 19-23) outline a series of steps to enable the better use of air quality data.

Integrating air quality measurement: Air quality monitoring technology and methods are rapidly developing and disparate data sources (e.g. regulatory-grade monitors, WNTs, ENTs, and satellite remote sensing) produce different, sometimes inconsistent, information. Regulatory-grade air monitoring stations often offer the most accurate measurement source, but at a single point with limited spatial representativeness. WNTs or ENTs, in a network or on a mobile platform, offer measurements across a broader area, but with lower accuracy. Satellite remote sensing offers observational information across an entire country and beyond, but has lower spatial resolution as well as fixed time windows and is more complicated to interpret. Integration of these different measurement platforms offers the opportunity to capitalise on their attributes to have an enhanced understanding of air quality.

Quality Assurance Considerations: The importance of quality assurance planning and execution in air monitoring cannot be overstated. The key quality assurance/quality control (QA/QC) elements in air monitoring involve the establishment of data quality objectives (e.g., data completeness), standard operating procedures (SOPs) for instrumentation and analytical laboratory processes, appropriately trained personnel, data management, and data reporting. Several sources of information exist for traditional air monitoring practices, including EPA's Air Monitoring Technology Information Center (AMTIC). For WNTs and ENTs, similar quality assurance principles apply, but need to take into account additional steps required to build confidence in the data (e.g., correction for measurement artefacts). The cost and efforts involved in data collection may be undermined if QA is not treated as essential - common failures include:

- the loss of fidelity of integrated $PM_{2.5}$ filter samples through improper handling,
- an incorrect flow rate leading to erroneous size-selection of particles entering an inlet,
- unreliable data from WNTs or ENTs if not demonstrated or calibrated against reference monitors in the LMIC environment.

Successful air monitoring requires a rigorous QA/QC system and ongoing training of staff involved in air quality data collection and dissemination.

Data Management, Dissemination, and Analysis: The goals of air quality data management are to:

- archive data sets for access in perpetuity,
- carefully track the data through the quality assurance process,
- communicate and raise awareness about air quality and human health.

A data management plan is critically important to a successful monitoring effort and should be considered while developing the monitoring strategy. An archive is a long term, redundant data storage system that guarantees the data will be available in the future. In the simplest form, data are recorded in a logbook, entered into a spreadsheet, and replicated electronically. It is critically important to also archive any meta-data about the location, timing, and quality checks needed to interpret the data.

In addition to archiving, a data management plan should include a protocol for data access, defining who has permission to access which datasets. Quality assurance specialists and auditors need to access and edit the data to provide quality flags or corrections. Air quality analysts need broad access to both the pollutant concentrations and meta-data about quality checks or corrections. Programmatic access to the data allows third party developers to build additional tools for visualising and analysing the data or creating specialized alerts. Making this data available to academia and other researches can go far to strengthen understanding of the challenges and solutions in addressing air quality impacts.

Finally, making air quality data available to the public builds awareness and unlock myriad uses of the data for public good. It is important to carefully develop the communication strategy, such that people have information that is comprehensible and actionable

Historically, a data management system would require procurement of computers, software, and services; however, this approach is challenging to set up, expensive to maintain, and difficult to scale as the monitoring network grows.

EPA's AirNow International project freely provides information on how to develop a system that includes archiving, data access for practitioners, and public communication (airnow.gov). The features and complexity of AirNow are beyond what is needed by most countries starting a monitoring network, though several pilot projects are underway to better understand how AirNow could meet these needs. A more lightweight system that takes advantage of open source communities, reduces maintenance complexity using cloud computing, and leverages standardised programmatic interfaces deserves further exploration and development. Air Qo in Uganda is providing such a service.

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